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A computerized method of vector triangulation for determination of horizontal wind profiles and shear in the stratosphere is described. Positions in photographic images of sunlight-scattering smoke trails released from rockets are automatically recorded by a digital video densitometer operating in an on-axis mode, from which three-dimensional positions are obtained.

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20. Abstract (continued)

Requirements for accuracy of location and 3-axis orientation of the triangulation cameras, needed to provide 10 meter altitude accuracy, are outlined. A logic design for a new generation hardware system is presented.

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FOREWORD

The program described here involved identification of requirements for atmospheric data to meet DoD needs in the area of effects on military systems of the radiations from nuclear explosions. Work on measurements of stratosphere dynamics, which is applicable to understanding of natural turbulence structure, is reported. Improvements in the implementation of photographic triangulation techniques were devised which permit more precise measurements of atmospheric winds and transport from observations of rocket deposited smoke trails.

Scientific Report NO.1 on this program, "Ultraviolet Sky Backgrounds Following F-Region Energy Deposition (S) AFGL-79-0260, was submitted on 31 Oct 1979.

The authors express their thanks to R.E. Huffman, R.E. Good, and A.F. Quesada and W.K. Vickery for their continued encouragment and support, and to C.C. Rice who helped in preparation of this report.

SECTION I

ANALYSIS TECHNIQUES

The techniques applied to determine that atmospheric wind field with very high resolution, using sets of photographs of sunlight-scattering smoke trails released from rockets, are reviewed and applied here. Further details of the measurements and results analyzed appear Ref 1 (these data have been communicated to AFGL staff and are not repeated here).

SMOKE TRAIL TECHNIQUE

Remote sensing of atmospheric winds and turbulence by analysis of the motions of tracers has been performed for at least 20 years, for altitudes ranging from the troposphere to the thermosphere. The method assumes that the tracer trail, either a dense chemical smoke or a sunlight-scattering or self-luminous (by reaction with ambient species) gas released from a sounding rocket, is transported substantially intact by the wind field for periods of one to two minutes, which is sufficient to determine an altitude profile of average wind over that time. This assumption is usually not valid over longer observation periods as evidence of turbulent transport of the tracer material becomes predominant. Turbulence parameters can be similarly determined from the growth of the "width" of the luminous trail.

We concentrate here on smokes released at statospheric altitudes. Precisely timed photographic records of smoke trail

position as a function of time are taken concurrently from a minimum of two observation si-es, which ideally are located to minimize triangulation errors by optimizing the base leg (site separation). Long focal length cameras with high-precision optics and large film format are used to obtain the maximum possible precision of the spatial information. The time of each exposure is recorded on the film frame, and must be accurate to within 1/10 sec to be consistent with the accuracy of the camera orientation (pointing) determination described later. Also exposed on each film frame are small fiducial markers providing the definition of a film plane coordinate system which is fixed with respect to the camera optic axis and serves as the basis for all subsequent digital measurements of the film. Time dependent trail positions determined by triangulation from these photographs are then used to calculate horizontal winds as a function of altitude.

PHOTOGRAPHY

Accuracy of the wind measurements of course depends on the quality of the photography of the trails themselves and the star field calibration photographs used to determine camera orientation. Data on the planned rocket trajectory, release altitude, and camera geographic coordinates are used to precalculate (approximately) the azimuth and elevation of

the optic axis of each camera used. Calibration photographs of the star background are usually exposed during the night immediately prior to the release, and exposures are also made on the night following the release.

Redundancy in calibration serves a two-fold purpose One purpose is to insure that the camera has not been moved inadvertently, and the other is to allow the camera to be positioned to a new orientation if the smoke trail turns out not to be initially in its field of view. Early attempts to achieve very high vertical resolution (<20 m) in wind profiles demonstrated that even very minor inadvertent motion of one or both of the triangulation cameras after the calibration was performed could render the reduction at these scales suspect, making the winds subject to large errors. Considerable care must be taken to eliminate camera motion which may be caused when placing protective covers on the cameras, slight jarring when covering or uncovering lenses, changing aperture ratio, or even strong gusts of wind. The primary purpose of the second star calibration is to provide confirmation of the stability of the camera mounting system, and is also indicative of the degree of caution exercised by the camera operator.

DIGITIZATION

Digitization of star locations and film plane trail positions is accomplished using a semiautomatic computer controlled microdensitometer (Ref's 1,2). This is a video-based system with an encoded stage which the computer transports to align the optic axis of the video camera with any point of the film image. Electronics for processing the video signal provide either linear (film transmission) or logarmithic (film density) presentation of the image information, and has adjustable operating ranges of approximately 0.5, 1.0, 1.5, and 3.0 optical density units. These ranges may be shifted, if desired, to cover any portion of the total useful range (4D) of the densitometer instrument. The system is unique in that gross alignment of features to be measured may be accomplished using distances and densities from the off-axis video while fine positioning and measurement of the densities of the features is performed on the video axis as the film is transported by the stage. That is, effects of field curvature/distortion, and of system photometric non-uniformity (vignetting), are essentially removed by working always on the optic axis. Final coordinate information is obtained only from the extremely accurate stage drive and encoders (less than 10μm total error over 150mm, repeatability and precision better than 2μm).

The digitization procedure first aligns the film frame

on the scanner by using two fiducial markers, such that one axis of the film is orthogonal with one axis of the scanning system. Measurement of a third fiducial then establishes the film plane coordinate system whose center lies on the camera optic axis. Trail digitization starts with input of a trail "skeleton," a series of guide points widely spaced along the trail image which are entered by using a joy stick control to transport the film to the desired positions. These points provide starting and ending points for the curve follower software of the computer system, and allow both fine scale determination of the coordinates of the trail axis and incrementing along the trail with minimal operator intervention.

Star calibration photographs are made with long exposures (2 min), during which time each star produces a narrow arc segment or star track on the film as a result of the earth's rotation during the exposure time. The coordinates of the center point of each track (corresponding to the midpoint of the exposure) are found by first digitizing and storing a series of coordinates and densities which trace the axis of the track. Density and position information is then processed to determine the end points of the track axis, and the position of the center of the arc length (star center) is calculated. Utilizing star tracks generally provides star locations to a higher precision than that obtainable from point star images recorded with short duration exposures.

CAMERA ORIENTATION

The accuracy of the wind measurements depends on the accuracy with which is determined the orientation or pointing angles of the cameras. For example, to resolve segments of a trail at 10 meter (±5m) vertical resolution at a 50 km range, angular errors of no more than 0.005° can be tolerated. Fortunately, when there is considerable pointing error there are usually clear indications of this effect during triangulation and velocity determination, primarily appearing as abrupt discontinuities in trail position that result in overly large wind shears. Optimization procedures may be applied in an attempt to reduce errors of this type; trail and wind discontinuities can be reduced in magnitude but of course there is then no assurance that the angles obtained (and therefore the winds) are indeed correct. The optimization techniques can produce a family of angular solutions which meet the required conditions, but obviously produce different wind fields.

Observation camera parameters are found using vector methods (Ref 4) of solution that relate the star image positions in the film plane to the equatorial coordinates of the stars (precisely known from star catalogs) at the same time. Besides knowing the time at which the calibration photograph was exposed, the camera location on the earth's surface (latitude, longitude, and altitude) must also be accurately known.

This is usually taken from geodetic survey information, with a target accuracy of 10 meters. Camera azimuth, elevation, horizonal tilt, and the precise focal length of the lens are determined, and through editing of the input star coordinates and iteration of the parameter determinations, the standard deviations associated with each parameter are reduced to levels consistent with the desired triangulation accuracy. For the cameras usually employed to determine atmospheric winds (18 cm film format and 18 cm nominal focal length) angular standard deviations of 0.005° and 0.01 cm focal length standard deviation may be routinely achieved. These deviations, considered as spatial accuracies, are on the order of 5 meter error at the typically 50 km range to a stratospheric smoke trail.

TRIANGULATION AND HORIZONTAL VELOCITY MEASUREMENTS

The triangulation procedure proper uses digital film plane coordinates of the trail centerline as viewed from two sites, the site locations, and the camera orientations derived from the star calibration photographs. In principle it is possible to reconstruct the spatial location of the trail from these photographic projections, using plane or spherical trigonometric triangulations. More recently, advanced techniques utilizing vector and matrix methods described in Reference 5 have significantly improved the accuracy of triangulation and of the smoke trail method. The practical application of triangulation methods, however, encounters numerous problems, some of which are detailed in Ref 3.

Release trails generally have no features which can be uniquely identified in two or more photographic projections. Triangulation is therefore performed using an iterative approach to determine a minimum error correspondence of the digital film plane trail positions of one site with the positions recorded from the second site. The quantity which is minimized is a dihedral angular mismatch (actually a figure of merit involving two unit normal vectors) between two planes. Each plane is defined by the common line through the two observation sites and the point line of sight vector from each site for the film plane trail points which are being test matched. The spatial position of the trail (in altitude, latitude, and longitude) is determined using a spherical earth model from the intersection (or near intersection) of the line of sight vectors for matched points. These data are then stored for later use by the computer program which determine horizontal velocities from time sequential trail positions.

The final step of the smoke trail procedure is determination of winds from the point trail positions. The trail position data from triangulation are interpolated to equal-altitude spacing by either cubic interpolation or spline fitting, and then least squares analysis of position versus time is used to derive average horizontal velocities from a time sequence of positions (usually five times spanning a period of one to two min).

SECTION II

COMPUTER PROGRAM AND HARDWARE MODIFICATION

This Section describes improvements to the computer software, hardware difficulties encountered, and the specification of new hardware to update the Coordinate Measurement System. A major improvement in the computer tirangulation was programmed and tested, and the least-squares velocity analysis was revised.

TRIANGULATION

The improvement in the computer triangulation scheme is primarily the result of a change in methodology which demands that point matching be accomplished to a much higher accuracy than previously. The result is that about 60% of the digitized points are discarded during the triangulation, a number previously considered to be unacceptable. Furthermore, the altitude resolution obtained is approximately 20 meters for data which was digitized at about 5 meter resolution. Other measures of "goodness of fit" of the triangulation -- average film plane mismatch and average separation vector -- have been improved by a factor of ten. There is now also excellent agreement between velocity profiles calculated from triangulations of site 1 with site 2 or the reversed pairing of site 2 with site 1.

Further study of the change made to the triangulation procedure -- that is, the insistence that dihedral angular mismatch be extremely small -- showed that it effectively preserves trail

continuity. Larger values of dihedral mismatch permitted an accumulation of error to occur until the limit was reached, followed by several consecutive mismatches, and then again followed by error build up. The resulting sawtooth error would always generate small discontinuities, and occasionally larger ones which proved to be very troublesome. Because of the small percentage of matches when using the small dihedral angle criterion, it is estimated that in order to maintain an average 10 meter vertical resolution, the film data must be digitized at intervals of no more than 12μm (for 40 km range). This interval can be made larger or smaller dependent on the degree of distortion of the trail by the wind field.

A slight reduction in the digitization workload could perhaps be realized by digitizing the films from one site at the nominal 10 meter resolution and the other site at higher resolution (approximately 2.5 meters). We recommend that a test be performed to determine the actual resolution achieved from such "unmatched" pairs of film plane data.

With the advent of this change in triangulation procedures, the major error source in determining trail positions and subsequently velocity is now the precision with which camera orientation can be measured. We recommend also that a method be devised to automatically make the two-min star calibration exposures and

record the start and end times of the exposure to < 1/10 second accuracy. Increasing the number of stars used (currently 10 to 15) and decreasing the digitizing interval used on the stars (typically 20μm) would also contribute to more precise measurement of orientation.

As part of an ongoing process of improvement, a log of failures or shortcomings in the coordinate digitization software and hardware is maintained. Review of the log indicates areas which need modification to enhance system performance.

Minor changes were made to the least squares velocity analysis routines to correct several inconsistencies which depended on the treatment of the time separation of the sequential trail positions. The velocity measurements were unaffected by the change, but the uncertainty of error associated with each velocity was reduced by nearly a factor two.

HARDWARE

Many of the hardware problems discussed in Reference 1 have persisted or grown progressively more severe. Failure of two major system components eventually forced a halt to new trail digitization because of the unreliability of the positional information obtained.

The video camera began to show extensive sensitivity to normal 2 - 3°C variations in ambient air temperature. The

operation of the system depends upon the stability of the relative optical density measurements provided by the camera and log amplifier -- output drift rates of approximately 5% (10 - 15 units) of the total output range (0 - 255) per minute cannot be tolerated. Repeated conversations with the manufacturer could not isolate the problem and eventually the camera was returned to the manufacturer for overhaul.

Concurrent with the camera problem, the digital line buffer which provides the interface between the computer and the disk storage unit repeatedly failed to transfer data properly which would result in computer program termination. The cause of these failures was difficult to determine because they would usually only occur every 15 - 20 minutes. Furthermore, if a suspected cause of the problem was located replacement of an integrated circuit was a very time consuming procedure. Approximately 90% of the 250 integrated circuits in this unit were obsolete. Replacement then required rewiring to accommodate a circuit with similar function but different pin configutation.

Because of the age, unreliability, and servicing difficulty a survey of replacement equipment was undertaken. Parts of the system which were either new or operated essentially trouble free would be retained.

Factors involved in the choice of equipment recommended

were demonstrated reliability, ease of interfacing (plug compatibility where possible), ease of existing software conversion, and manufacturer service support. Further consideration was given to equipment which would enhance system operation -- not just replace existing hardware. The recommendations made are shown in the outline in Figure 1.

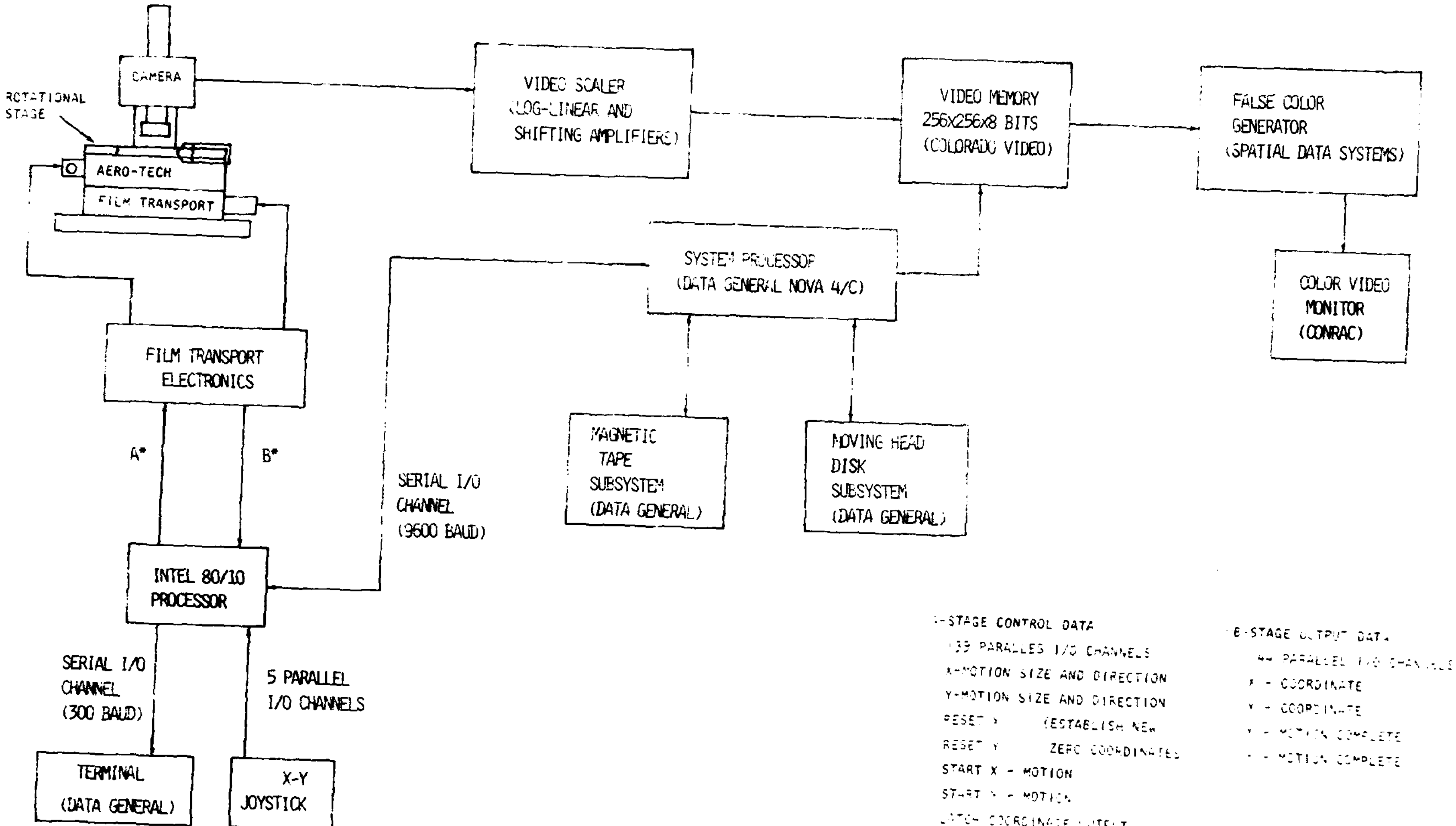

FIGURE 1. Block diagram of the Coordinate Measurement System

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